Application of an Optimization/Simulation Model for the Real-time Flood Operation of River-Reservoir Systems with One and Two-Dimensional Unsteady Flow Modeling

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Research Article

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Abstract

An application is presented of a new methodology for the real-time operation of flood control reservoir gate control operations of river-reservoir systems to minimize flooding. The methodology is based upon an optimization/simulation modeling approach that interfaces optimization with a one and/or two-dimensional unsteady flow simulation model (U.S. Army Corps of Engineers HEC-RAS). The approach also includes a model for short-term rainfall forecasting and the U.S. Army Corps of Engineers HEC-HMS model for rainfall-runoff modeling. Both short term forecasted rainfall in addition to gaged streamflow data and/or NEXRAD (Next-Generation Radar) can be implemented in the modeling approach. The optimization solution methodology is based upon a genetic algorithm implemented through MATLAB. The application is based upon the May 2010 flood event on the Cumberland River system in the USA, during which releases from Old Hickory dam caused major flooding downstream area of Nashville, Tennessee area. One of the major features of the modeling effort and the application presented was to investigate the use of different unsteady flow modeling approaches available in the HEC-RAS) including one-dimensional (1D), two-dimensional (2D), and the combined (1D/2D) approach. One of the major results of the application was to investigate the use the different unsteady flow approaches in the modeling approach. The 2D unsteady flow modeling is based upon the diffusion wave approach was found to be superior for the application to the Cumberland River system

1. Introduction

Several models for reservoir operation, that include flood control as one of the purposes, and based upon optimization have been developed over the years, as reviewed in detail by Che and Mays (2015). However, there have been only a very few optimization approaches interfaced with unsteady flow simulation models that consider the real-time flood-control operation (gate control operations at dams) of river-reservoir systems. There are even fewer approaches that interface simulation models: (a) for rainfall-runoff analysis using both actual rainfall and predicted short term future rainfall and (b) for unsteady flow propagation of floods through river-reservoir systems. Models that do have this ability include those developed by Unver, et al. (1987), Unver and Mays (1990), Ahmed and Mays (2012), Che and Mays (2015, 2017). These approaches have been reviewed by Che and Mays (2015) and are the basis for the newer and expanded model reported by Albo-Salih and Mays (2021).

Recent efforts at developing methods for flood control operation based upon optimization include Cuevas-Velasque eta l (2020), Zha et al. (2021), and Zhou et al. (2018). Recent efforts at developing methods based upon optimization and a one-dimensional model for the hydraulics include Nguyen (2020) and Xu, et al. (2021). New risk-based models include those by Chen et al. (2018), Sun et al. (2018), Uysal et al. (2018), Chen et al (2019a), Chen et al (2019b), and Lu, et al. (2020). However, none of the above recent efforts have the capabilities of the modeling of real-time flood control operation of reservoirs reported herein and by Also-Salih and Mays (2021).

The mathematical formulation of the model implemented in the application is presented in the Appendix.

2. Cumberland River Basin

The Ohio River System is illustrated in Figure 1, which also shows the location of the Cumberland River and Nashville, Tennessee. The Cumberland River Basin, shown in Figure 2, is located entirely within the states of Kentucky and Tennessee, and has a total area of 17,914 mi^2 miles, of which 10,695 square miles (60%) are in the state of Tennessee. The topography of the Cumberland River Basin changes from rugged mountains in the eastern upstream portion of the basin to rolling low plateaus in the western, or downstream part of the basin (USACE, 2010c and 2012).

Five projects on the Cumberland River mainstream are maintained and operated by the U.S. Army Corps of Engineers Nashville District, plus five other projects on the tributaries. The mainstream projects are the Cordell Hull, Barkley, Cheatham, Old Hickory, and Wolf Creek. Wolf Creek and Barkley, shown in Figures 2 and 3, are the only congressionally authorized project, in terms of flood risk management, while Congress authorizes Barkley, Cheatham, Old Hickory, and Cordell Hill for hydropower generation and commercial navigation. The five Corps of Engineers tributary projects, Dale Hollow, Center Hill, Martin's Fork, Laurel, and J. Percy Priest, shown in Figures 2 and 3, are congressionally authorized for flood risk management (USACE, 2010c and 2012).

3. Flood Event Of May 2010

Weather disturbances in the mid-level atmosphere contributed to trigger storms producing heavy rainfall over the mid-Mississippi and Lower Ohio Valley regions (NWS, 2011b). This rare convergence of conditions was obviously favorable for a large, prolonged and powerful, rainfall event over the central Continental U.S. caused the May 2010 historic precipitation across Tennessee and Kentucky. Composite high-resolution precipitation images for April 25-30, 2010 indicated the extreme severity of rainfall several days in advance of the flooding (U.S. Army Corps of Engineers, 2012). On April 30th, a very intense storm system moved into the central parts of the United States, and unfortunately, these precipitation images (warnings) for April 25-30 were ignored by the U.S. Army Corps of Engineers (USACE). Had the USACE not ignored these warnings they could have started drawdowns at the Old Hickory Reservoir, which is immediately upstream of Nashville, in particular, and also at other upstream reservoirs.

3.1 Rainfall

Two episodes of heavy intense rainfall across Kentucky, and western and middle Tennessee, where between 10 to 20 inches of rain fell within 36 hours on May 1st and 2nd, causing catastrophic flooding events. The heaviest rains fell primary on unregulated portions of the Cumberland River Basin, downstream of the reservoirs containing sufficient flood control storage to help contain the event's runoff and mitigate flood damages (NWS, 2011b). Figure 3 shows the total rainfall over May 1st and 2nd, 2010. Hourly and accumulative rainfall data at the Nashville International Airport are shown in Figure 4. In Nashville over 13 inches of rain was recorded during a 36-hour period; 6.23 inches on May 1st, the 3rd highest 24-hour total ever on record, and 7.25 inches on May 2nd, which exceeded the previous 24-hours rainfall record of 6.60 inches set in September 1979 (NWS, 2011b). The highest weekend rainfall total was reported by the National Weather Service (NWS) Cooperative Observer in Camden, Tennessee at 19.41 inches.

3.2 Operation of Old Hickory Dam during 2010 Flood Event

Figure 5 shows the discharge from Old Hickory dam and the flood stage at the Nashville, Tennessee gage, as a function of time, during the April 29 – May 7, 2010 event. The Cumberland River at the Nashville gage rose more than 33 ft to a peak stage of 551.86 ft on May 3. According to Figure 3 the flood stage of 45 ft was exceeded by 6.86 ft at the Nashville gage. As stated above, had the USACE not ignored the warnings of the composite high-resolution precipitation images for April 25-30, 2010, they could have started drawdowns at Old Hickory days in advance of May 1.

4. Optimization/simulation Model For Real-time Flood Control Operation

The overall mathematical formulation of the optimization/simulation modeling approach is a real time optimal control problem in which reservoir releases represent the decision variables and the spillway gate operations represent the state variables. The basic objective of the optimization/simulation model approach, illustrated in Figures 6(a) and (b) for river-reservoir system operation in real time, is to keep the discharges and/or water surface elevations below specified or target values at various locations during an extreme storm event.

Figure 6(a) illustrates the over model structure and interconnection of the model components. The optimization/simulation model includes four individual simulation models interfaced through MATLAB that make up the larger simulation model as follows: a short-term rainfall forecasting model, a rainfall-runoff model (HEC-HMS), a one and/or two-dimensional unsteady flow simulation model (HEC-RAS), and a reservoir operation model, and Figure 6(b) illustrates the interconnection of the simulation models and the genetic algorithm for solution of the optimization model.

The model formulation in the Appendix is a real-time optimal control problem in which the gate operations defining the reservoir releases are the decision variables. The reduced objective function (unconstrained problem), equation (7) is not a well-defined continuous function and is amenable to GA solutions when the constraints are solved using the simulation models (HEC-HMS and HEC-RAS) each time the constraints need to be solved. Classical optimization methods such as the simplex method for linear programming and gradient-based methods for nonlinear programming require well-defined functions. Also, derivatives of functions are required for nonlinear programming. The genetic algorithm does not require derivatives; nor does it require well-defined continuous functions.

6. Model Application To The Cumberland River System

The optimization/simulation model for the real-time operation of river-reservoir systems has been applied to the May 2010 flood event on Cumberland River system near Nashville, TN. The main objective of this model application is to demonstrate the applicability of the model for minimizing flood damages for an actual flood event in a real-time fashion on an actual river basin. Another objective of the model application is to compare the results of using the three unsteady flow simulation scenarios: one-dimensional, two-dimensional (diffusion-wave model), and combined one- and two-dimensional (diffusion-wave model) utilizing HEC-RAS 5.7 as the simulation model for the unsteady flow. This allowed comparison of the three unsteady flow simulation methodologies used with the optimization procedure. The 100-year stage and water surface elevation at the Nashville, Tennessee gage are 48 feet and 417.52 ft, respectively; and the 100-year discharge is 172,000 cfs.

6.1 Model Set-up

The approximate watershed area of the Cumberland River system modeled in the USACE HEC-HMS model is 14,160 mi^2. The modeled watershed area included head waters of the basin starting in Lechter County, Kentucky downstream to Cheatham Dam (approximately around 30 miles downstream of Nashville). The HES-HMS input was developed by the U.S, Army Corps of Engineers (USACE) and consists of 66 reaches and 69 basins. The HEC-HMS was calibrated and validated for the May 2010 storm event by Che (2015) who compared the simulated and the observed Dale Hollow reservoir inflow hydrographs for the May 2010 storm event. The one-dimensional HEC-RAS unsteady flow model of Cumberland River system consisted of 675 cross sections, 8 inline structures, 117 lateral structures and 1 bridge. Che (2015) has also calibrated and validated the 1-D unsteady flow model for the May 2010 storm event.

The portion of the Cumberland River system modeled in the unsteady flow simulations for this application is shown in Figure 7. The purpose of this application is to illustrate how to minimize the flood damages at Nashville by keeping the flood stages (water surface elevations) under the 100-year flood stage of 48 feet at the Nashville Woodland station during the storm event. Operation of Old Hickory Dam was the major component in minimizing flood damages downstream of Old Hickory Dam.

The reservoir regulation and operation rules prepared for the U.S. Army Corps of Engineers Nashville District were used in the model to set the operation rules constraints. The HEC-RAS two-dimensional module based upon the diffusion-wave equations was selected over the full equation approach because the diffusion-wave 2-D approach is much faster and more stable. The speed of computations is very important because of the many simulations required in the optimization/simulation approach.

The optimization - simulation model was applied to a portion of the Cumberland River as shown in Figure 7. The real-time rainfall data source for the May 2010 flood event is the high resolution gridded generated by Next Generation Radar (NEXRAD) was used for the hydrologic modeling. The portion of the Cumberland River modeled in HEC-RAS using the two-dimensional approach is from Old Hickory Dam downstream through Nashville to Cheatham Dam.

6.2 Solution Process

The solution process starts with the available actual rainfall data up to time t for the area upstream from Cordell Hull and J. Percy Priest reservoirs. The MATLAB code sends the actual rainfall data to the U.S. Army Corps of Engineers HEC-HMS model to simulate the rainfall runoff process. The discharge hydrograph from the HEC-HMS model becomes the inflow for the Cordell Hull Reservoir. The inflow hydrograph enters the optimization and operation model to determine the optimal releases from the Cordell Hull dam gates. The model now calls HEC-RAS to route the releases up to Old Hickory reservoir, where it considered as the inflow to the Old Hickory reservoir. Once the inflow hydrograph for Old Hickory reservoir is determined, the operation and optimization model determine the releases for the next 4 hours from the Old Hickory Dam. The optimization model employs the genetic algorithm in MATLAB to generate the initial solution considering all the operating rules constraints described previously and, calls the unsteady flow model (HEC-RAS) to test the generated solutions which is the time series of the Old Hickory gates openings. The unsteady flow model routes through the gate openings at both reservoirs downstream to the Woodland station at Nashville. The process continues iteratively until the objective function is satisfied. Then the model steps to the next time $t + \Delta t$. The model continues to run until the last Δt of the storm.

The optimization model (GA) uses the last generation or the optimal solution at time t as the initial solution for time $t + \Delta t$ to reduce the search time of the next step. This saves around 17 minutes of computation time for each iteration for this application. This computational time savings may be very valuable in real-time river-reservoir operation under flood conditions.

The most important factor that could limit this model is the simulation time for the unsteady flow calculations for each time step and for each iteration of the GA of the optimization. Shorter simulation times allows the optimization model (GA) to increase the number of objective function evaluations, which means the number of times that the simulator (HEC-RAS) is called. Producing faster simulation model taking into consideration the accuracy of the mode was a priority of this research. The most time-consuming part of the overall model application are the unsteady flow simulations. Every factor that may affect the time of simulation time, including the mesh size, computation interval, mapping output and even hydrograph interval was considered.

To obtain faster two-dimensional unsteady simulations, the diffusion wave model was utilized using the current version of HEC-RAS instead of the full two-dimensional simulation. The portion of the Cumberland River modeled in HEC-RAS using the one- and two-dimensional approaches is from Old Hickory Dam downstream through Nashville to Cheatham Dam.

6.3 Operations of Old Hickory Dam

The time series of the gate openings at Old Hickory are the decision variables of the optimization–simulation model including the constraints of reservoirs constraints such as: gates openings discharge relationships, operation rules of the gates under flooding condition, the gate height hourly rate of change and reservoirs stage storage relationship. The model determines the operation for each forecasting period Δt, which is 4 hours for the of Cumberland River.

The actual operation of the Old Hickory Dam during the event started the releases at night on May 1, 2010 despite the forecast warnings from severe rainfall several days in advance. Using the optimization/simulation model with the available forecasting information could have helped the U.S. Army Corps of Engineers make decision at Old Hickory Dam before the actual storm entered the Old Hickory Reservoir in a timely manner.

6.4 Unsteady Flow Scenarios

Three scenarios were adopted to simulate the unsteady flow for the May 2010 flood event. The first scenario uses combined one- and two-dimensional unsteady flow modeling, in which the Cumberland River, Nashville reach has been model in one dimensional, while its flood plain was modeled using two-dimensional unsteady flow simulation. The two-dimensional area was divided into four sub regions, two the for the north side of the river reach and two for the south side and as NE, NW, SE and SW a shown in Figure 8. These sub areas were gridded into 832, 1068, 235 and 1208 cells respectively. The total area of these cells that cover the two-dimensional modeling is around 106 square miles. The input spacing into the 2-D flow area editor for generation of cells is 1000 x 1000 feet.

The other components include: two reaches, cross sections, storage areas, laterals, inline structures, and one junction. The Nashville reach connects Old Hickory Dam at the upstream to Cheatham Dam at the downstream using 76 cross sections over the total length of 51 miles. The other reach is Stone River reach that links the J. Percy Priest Lake to the Nashville reach via 22 cross sections. The cross sections were extracted from the terrain model and modified with the actual cross sections surveyed by U.S.AC.E. The terrain does not accurately represent the actual bathometry of a river reach because the LIDAR technology does not have the ability to penetrate water surface elevations.

Each of the two-dimensional areas is connected to the river reach (one-dimensional area) through a lateral structure. Figure 8 shows the combined one and two-dimensional areas downstream of Old Hickory and JPP, where the blue arrow illustrates the general flow direction from NE to SW. Each iteration of combined one- and two- dimensional model takes 5 to 6 minutes to run one unsteady flow simulation for this portion of Cumberland river system shown in Figure 9 is a simulated inundation map developed using the combined one- and two-dimensional approach in HEC-RAS for the May 2010 Flood Event. Figure 10 is a simulated inundation map developed using only the two-dimensional approach in HEC-RAS for the May 2010 Flood Event.

The second scenario uses only the two-dimensional unsteady flow modeling downstream of Old Hickory dam. One of the problems in using only the two-dimensional approach is that terrain data does not often include the actual terrain underneath the water surface in the channel region (river bathometry) due to the fact that LIDAR processing is not capable of penetrating the water surface elevation (U.S. Army Corps of Engineers, 2016c). As a result, many HEC-RAS users do not prefer only the two-dimensional approach. Thus, the terrain model of the only two-dimensional of the Nashville reach has been modified through RAS Mapper by creation of a terrain model of the channel region only from the cross sections surveyed and measured in field by U.S Army Corp Engineers and the cross-section interpolation surface.

The second scenario was set up with only two-dimensional area enhanced with 2-D break lines along the river reach to enforce the mesh generation tools to align the computational cell faces along the break lies. The two-dimensional flow element connected directly to the storage areas: Old hickory Reservoir and J. Percy Priest Lake using the storage area and 2-D area connections that allow to input the data of hydraulic structures such as gates to weirs as it set in normal inline structures to control the flow between the two elements of area. The 2-D area was divided into 3211 cells, with maximum cell area of 2.2 M square foot, minimum cell area of 439 K square foot, and the average cell area of 974165 square foot. The total area of these cells that cover the two-dimensional modeling is around 112.2 square miles. The input spacing into the 2-D flow area editor for generation these cells is 1000 x 1000 feet, which is considered relatively course, the reason behind that is any finer cell size will take longer time to run the simulation and that may cause exceeding the lead time in which the decision for reservoir releases has to be made. However, the model ran well with the suggested spacing.

Due to the limited availability of the LIDAR that were used to develop the terrain model for Nashville, the area upstream of Old Hickory Dam was modeled using only 1-D unsteady flow simulation. The terrain resolution used in the model was 2.5 X 2.5 feet which is considered high enough to produce more accurate and detailed hydraulic table properties for two dimensional computational cells and cell faces.

6.5 Comparison of Simulation Scenarios

All the simulation scenarios showed close simulation results for the flood situation at Nashville during the May 2010 flooding event. The optimization and the combined one- and two- dimensional simulation as well as the one-dimensional model successfully kept the discharge at or below 171,809 cfs, after 64 iterations. This peak discharge is only a little higher than the one-dimensional result of the simulation-optimization model of (Che, 2015) with 171,076 cfs.

Each simulation run of the combined one- and two- dimensional simulation required from 6 to 8 minutes for the 4-hour time interval, for which the optimization model could perform around 23 iterations. The inundation map of the observed water surface of May 2010 for Nashville simulated using the combined one- and two-dimensional simulation approach is depicted in Figure 11.

Contrary to expectations, the two-dimensional simulation model linked with the optimization model resulted in peak discharges that did not exceed 169,694 cfs during the entire period of simulation of May 2010 storm event. This two- dimensional unsteady flow model ran faster than the combined one- and two-dimensional, so the optimization model had more time to improve the solution. The reason why the previous model is slower than this one is because of the connection between the two-dimensional and one-dimensional areas, which is modeled as very long lateral structures.

The observed water surface elevations in the form of inundation map for the May 2010 event at Nashville using the two-dimensional unsteady flow modeling approach (HEC-RAS) is depicted in Figure 12, which shows the flood inundation area resulting from application of the optimization/simulation model using the two-dimensional approach.

6.6 Comparison of Optimized Operations

A comparison is now presented of the resulting optimized operations with the actual operations by the U.S. Army Corps of Engineers during the May 2010 flooding event. Figure 13 compares the optimized discharges at Nashville for the May 2010 Flood Event for the three scenarios of unsteady flow modeling. Figure 14 compares the 100-year and optimized water surface elevations for May 2010 flood event at Nashville for the three scenarios of unsteady flow modeling. Figure 15 illustrates the differences between the optimized and actual operations (flood gate openings) of the Old Hickory. For the simulations all flood gates at Old Hickory were all opened the same distance as compared to the actual operations which were also all opened the same distance. During the actual operation of the gates in the flood event the operators waited too late to open the gates. Figure 16 illustrates the optimized and actual releases at Old Hickory Dam during May 2010 flooding event. Figure 17 compares the optimized and actual flows at Nashville during the May 2010 flooding event.

Discussion

The Cumberland River application of the optimization/simulation for optimal operation of the Old Hickory dam only considered one control point which was located at Nashville. This was because the only recorded water surface elevations for the flood event was at Nashville for purposes of the application. However during an actual real-time application for a river-reservoir several control points may need to be considered making the combined one-dimensional and two- dimensional routing more accurate and more applicable especially if control points were located in the floodplain and not just on the mainstem of the river.

Conclusions

An optimization/simulation model has been developed to determine the optimal operation of gates (reservoir release schedules) before, during and after flooding events. The proposed optimization/simulation model consists of four individual models (interfaced through MATLAB) that make up the larger simulation model created in this chapter and are listed as follows: a rainfall forecasting model, a rainfall-runoff model, one and/or two-dimensional unsteady flow model, and reservoir operation model with genetic algorithm optimization model. The two-dimensional optimization/simulation approach uses the U.S. Army Corps of Engineers Hydrologic Engineering Center HEC-HMS and the HEC-RAS 5.0.3 version. The reservoir operation model is optimized using the genetic algorithm within MATLAB. Although the genetic algorithm requires many function evaluations (simulation runs of HEC-RAS) to reach an optimum solution, the approach has the significant benefit of being able to interface with simulators.

The HEC-RAS program allows the modeler to choose either the full two-dimensional equations or diffusion wave equations in two-dimensions to solve the model which are set as the default. In general, the two-dimensional diffusion wave equations have reduced computation times and have more stable properties than using the full two-dimensional equations. Even though, a wide range of modeling situations can be precisely modeled with the two-dimensional diffusion wave equation, user' can always test if the full two-dimensional equations are required for their specific situation by creating another run.

The complete optimization/simulation model was applied to a portion of the Cumberland River System in Nashville, Tennessee for the flooding event of May 2010. The objective of this application is to demonstrate the applicability of the model for minimizing flood damages for an actual flood event in real-time on an actual river basin. The purpose of the application in real-time framework would be to minimize the flood damages at Nashville, Tennessee by keeping the flood stages under the 100-year flood stage. This application also compared the three unsteady flow simulation scenarios: one-dimensional, two-dimensional and combined one- and two-dimensional unsteady flow.

Declarations

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Availability of data and materials: Data and materials will be provided when request upon.

Code Availability: Will be provided when request upon.

Ethics approval: Not applicable.

Consent to participate: All authors have consented to participate in this study.

Consent to publication: All authors have consented to publish the work reported.

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Figures

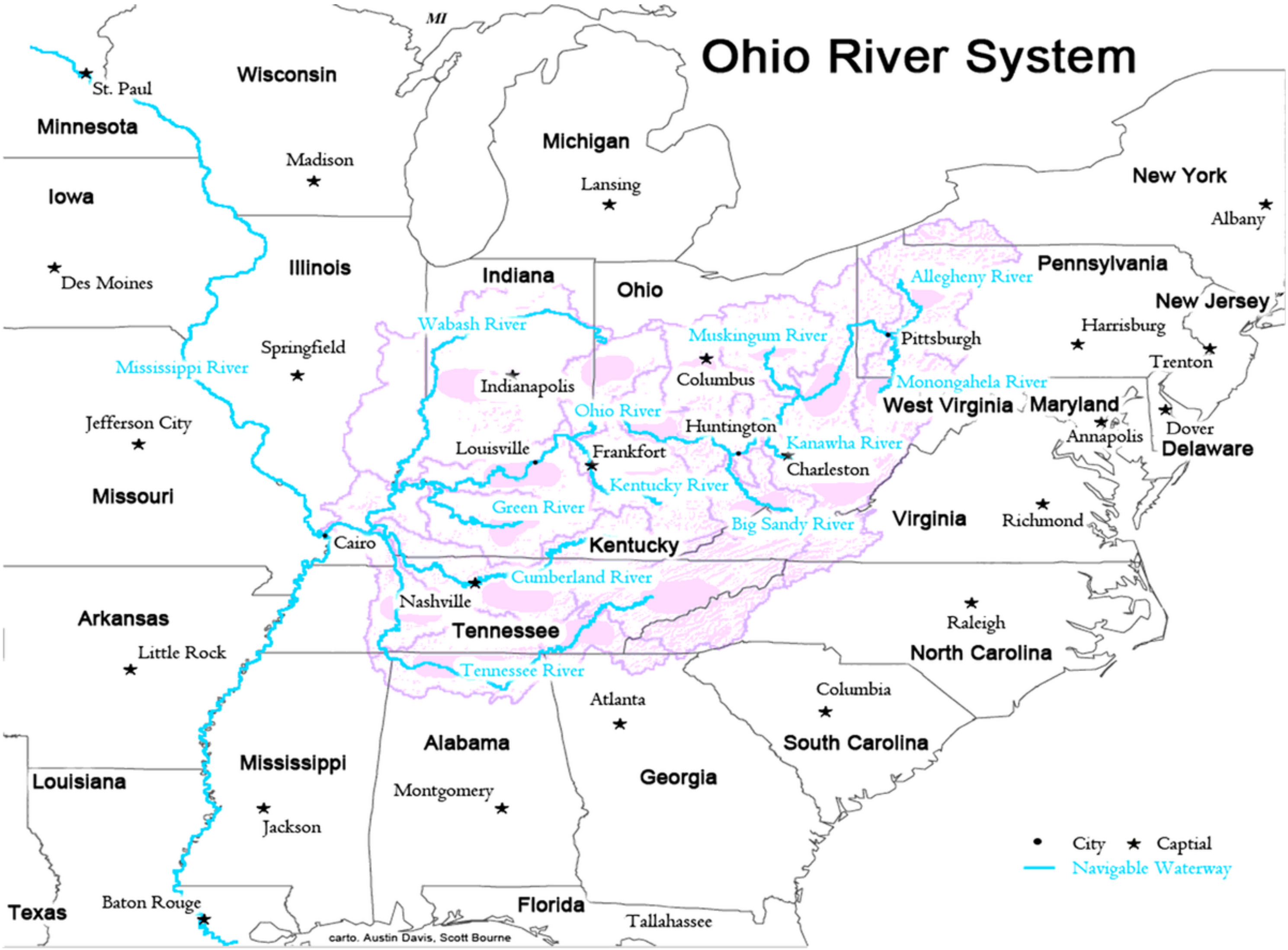

Figure 1

Ohio River System showing the location of the Cumberland River and Nashville, Tennessee (U.S. Environmental Protection Agency's, 2017)

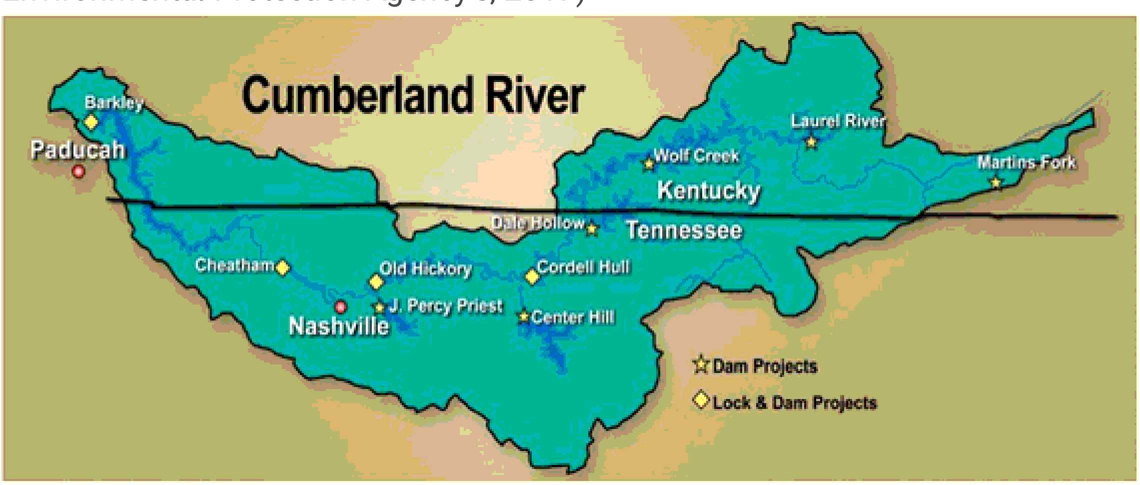

Figure 2

Cumberland River Basin with Dam Projects and Lock and Dam Projects (Source: U.S. Army Corps of Engineers)

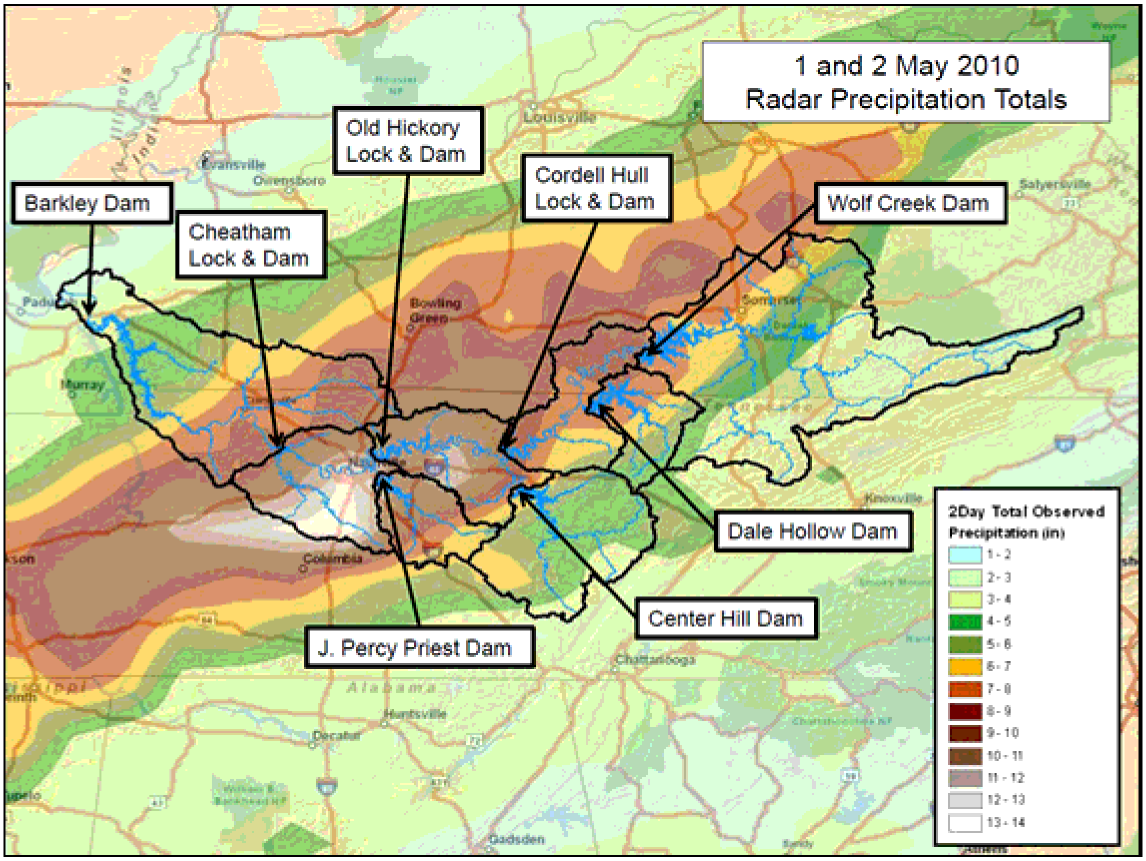

Figure 3

Location of Dam Projects in the Cumberland River Basin and the Total Rainfall over May 1st and 2nd, 2010, (U.S. Army Corps of Engineers, 2012)

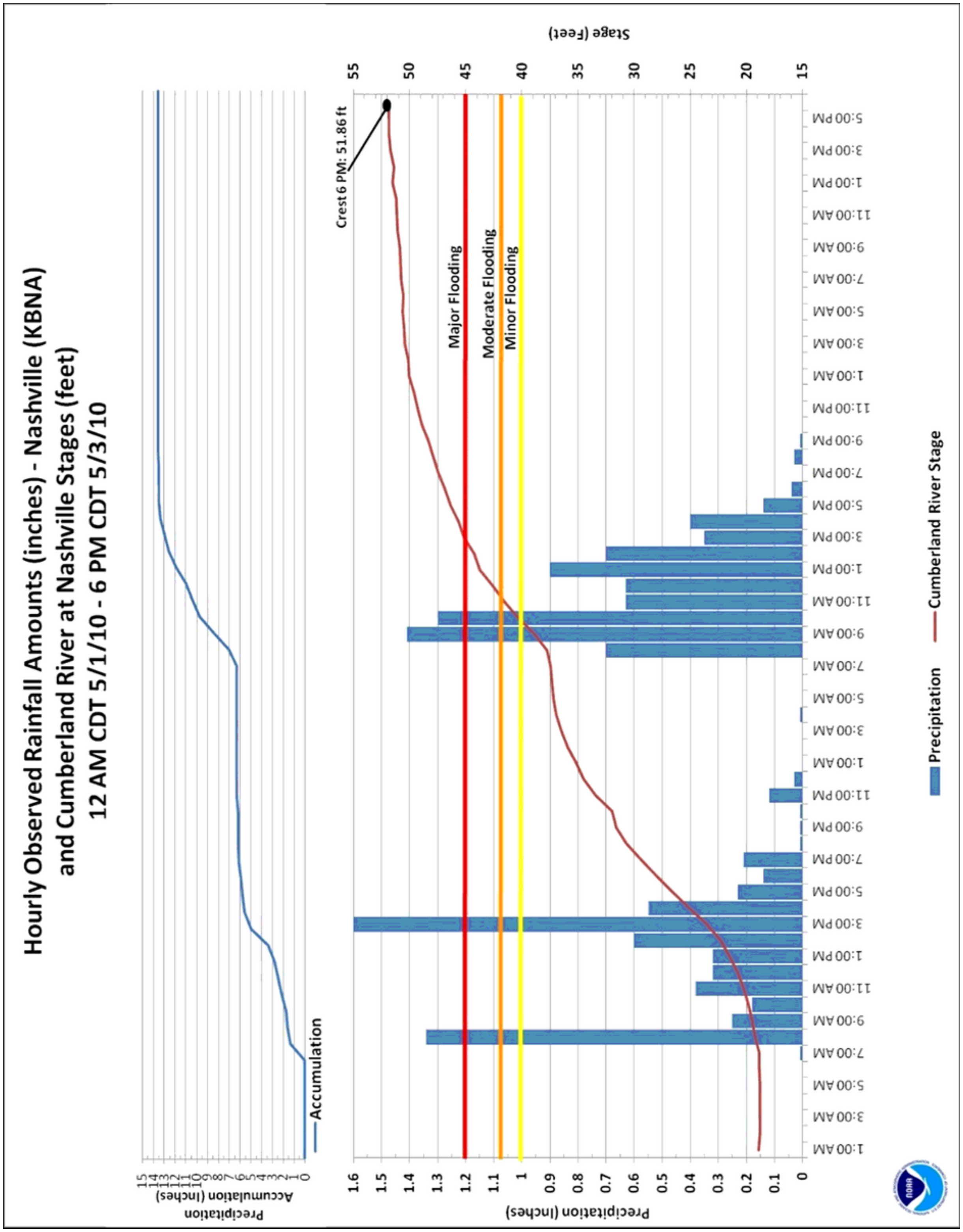

Figure 4

Hourly and Accumulative Rainfall at Nashville International Airport from 12:00 a.m., May 1st to 12:00 a.m., May 3rd. (U.S. National Weather Service, 2011)

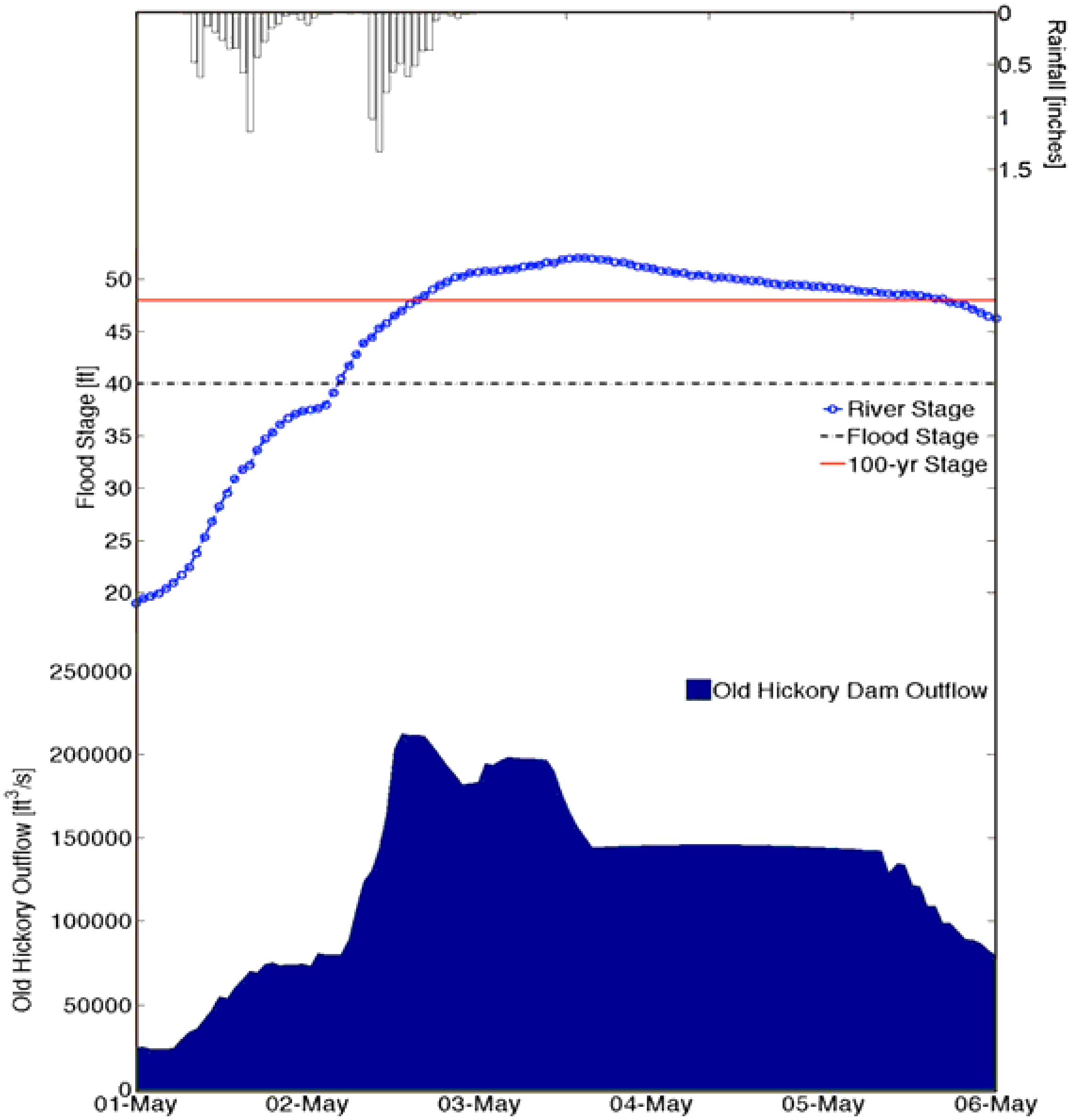

Figure 5

Discharge at the Old Hickory Dam and flood stage at the Nashville, Tennessee gage as a function of time during the April 29 – May 7, 2010 event. (U.S. Army Corps of Engineers, 2010a)

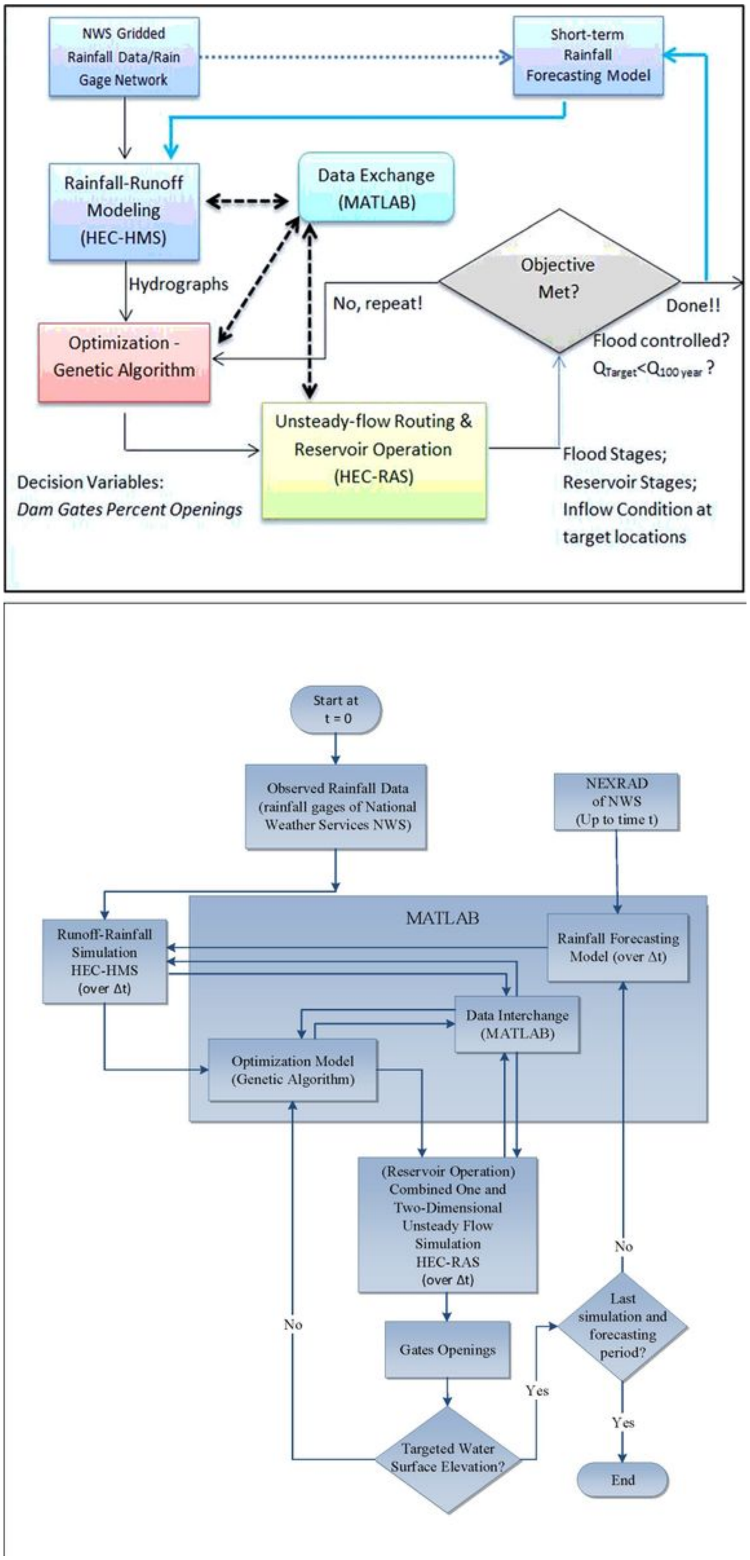

Figure 6

(a) Overall Model Structure and Interconnection of Model Components (Che and Mays, 2015) (b) Basic Steps of the Optimization/Simulation Model

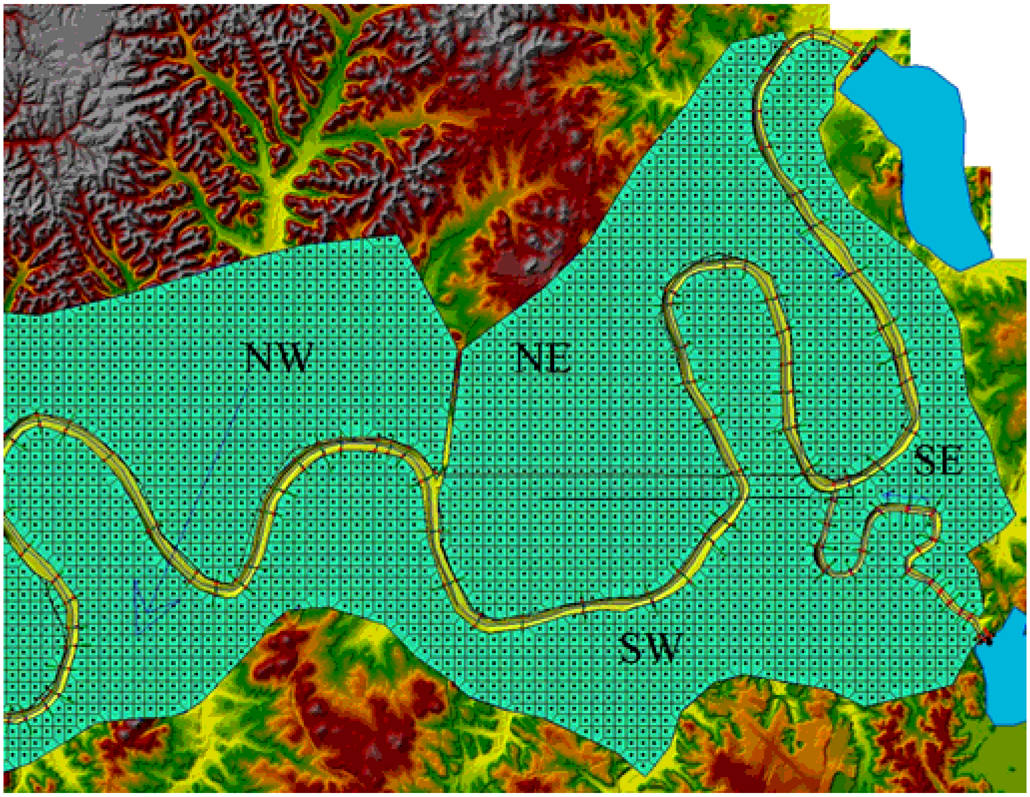

Figure 8

Combined One- and Two- Dimensional Areas downstream of Old Hickory and JPP (The blue arrow indicates the general flow direction from NE to SW)

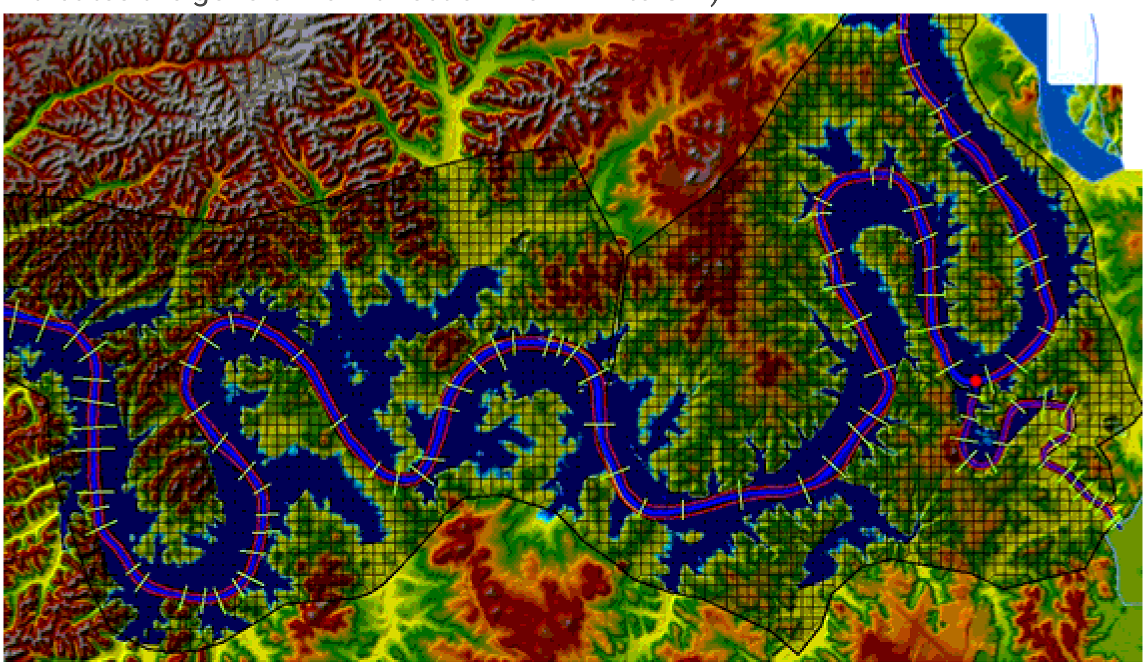

Figure 9

Simulated Inundation Map Using Combined One- and Two-Dimensional Approach in HEC-RAS for the May 2010 Flood Event

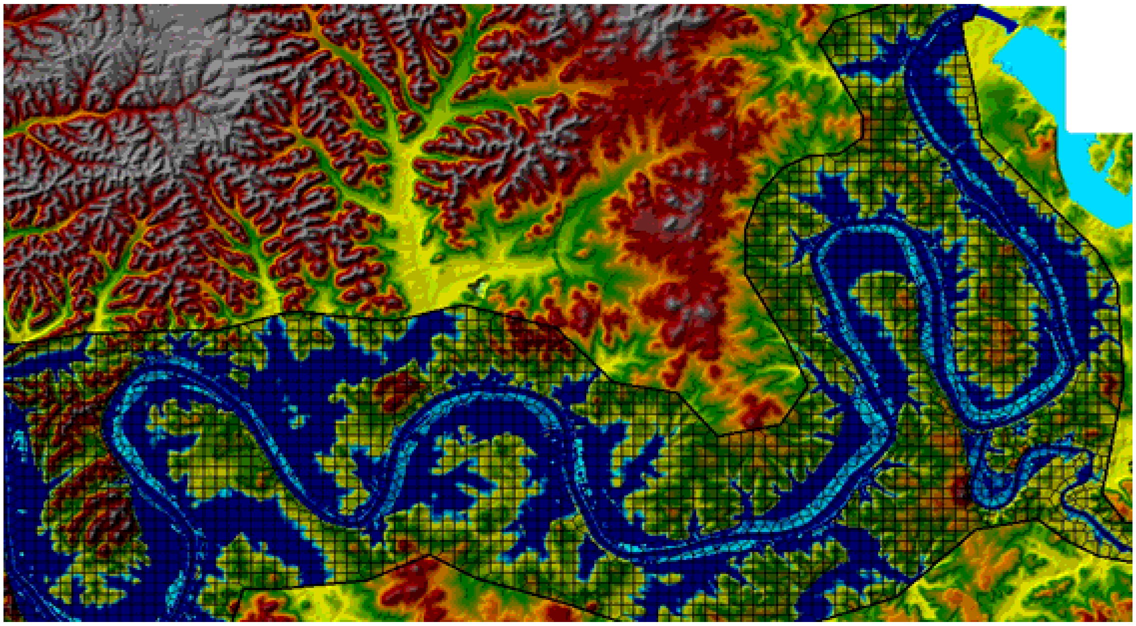

Figure 10

Simulated Flooding (Inundation Areas in blue) Using the HEC-RAS Two-Dimensional Approach for the May 2010 Flood Event

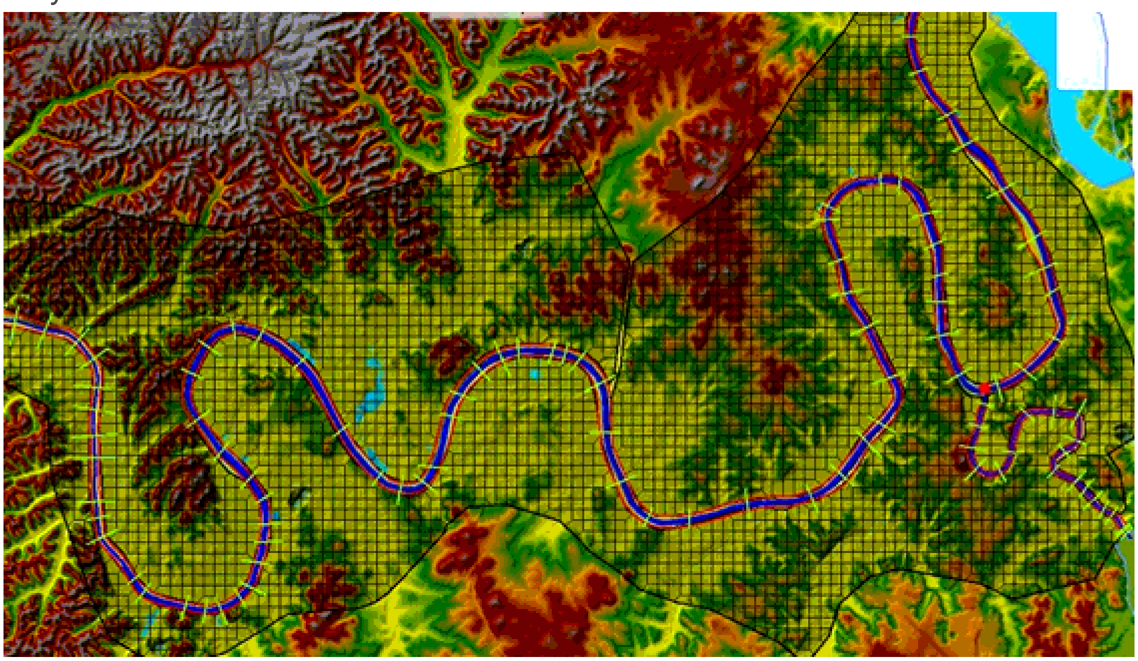

Figure 11

Optimized Inundation Area (shown in blue) Using Combined One- and Two-Dimensional Approach in HEC-RAS for the May 2010 Flood Event

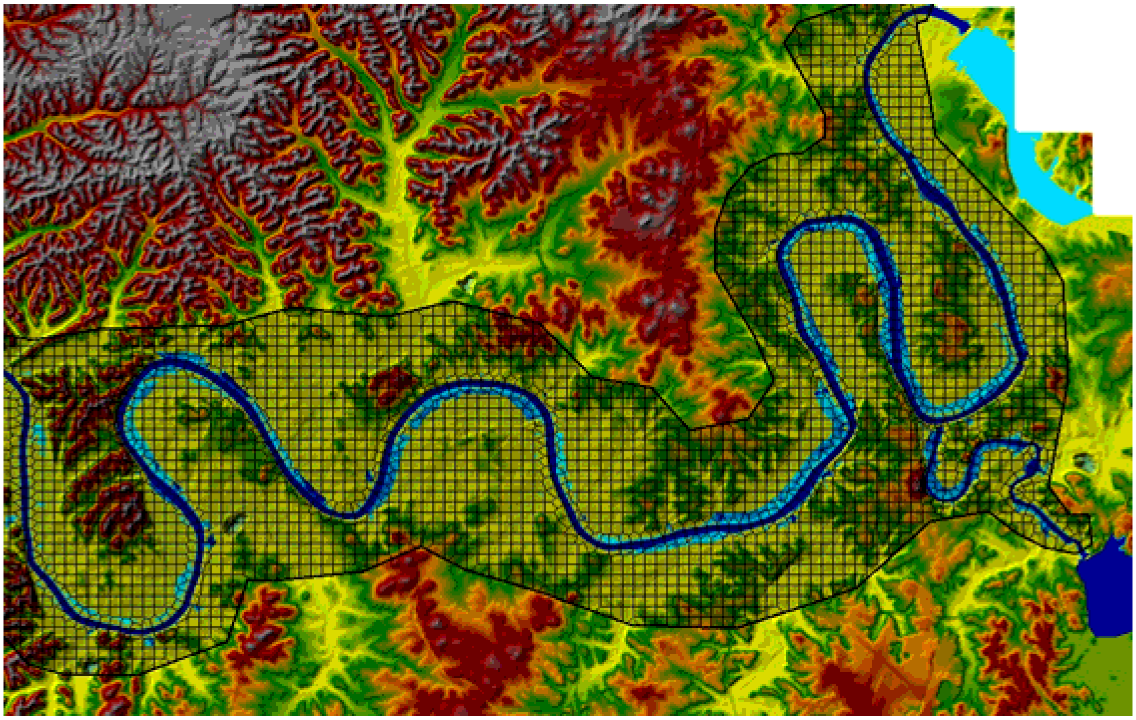

Figure 12

Optimized Flooding (Inundation Areas in blue) Using the Two-Dimensional Approach in the Optimization/Simulation Model for the May 2010 Flood Event.

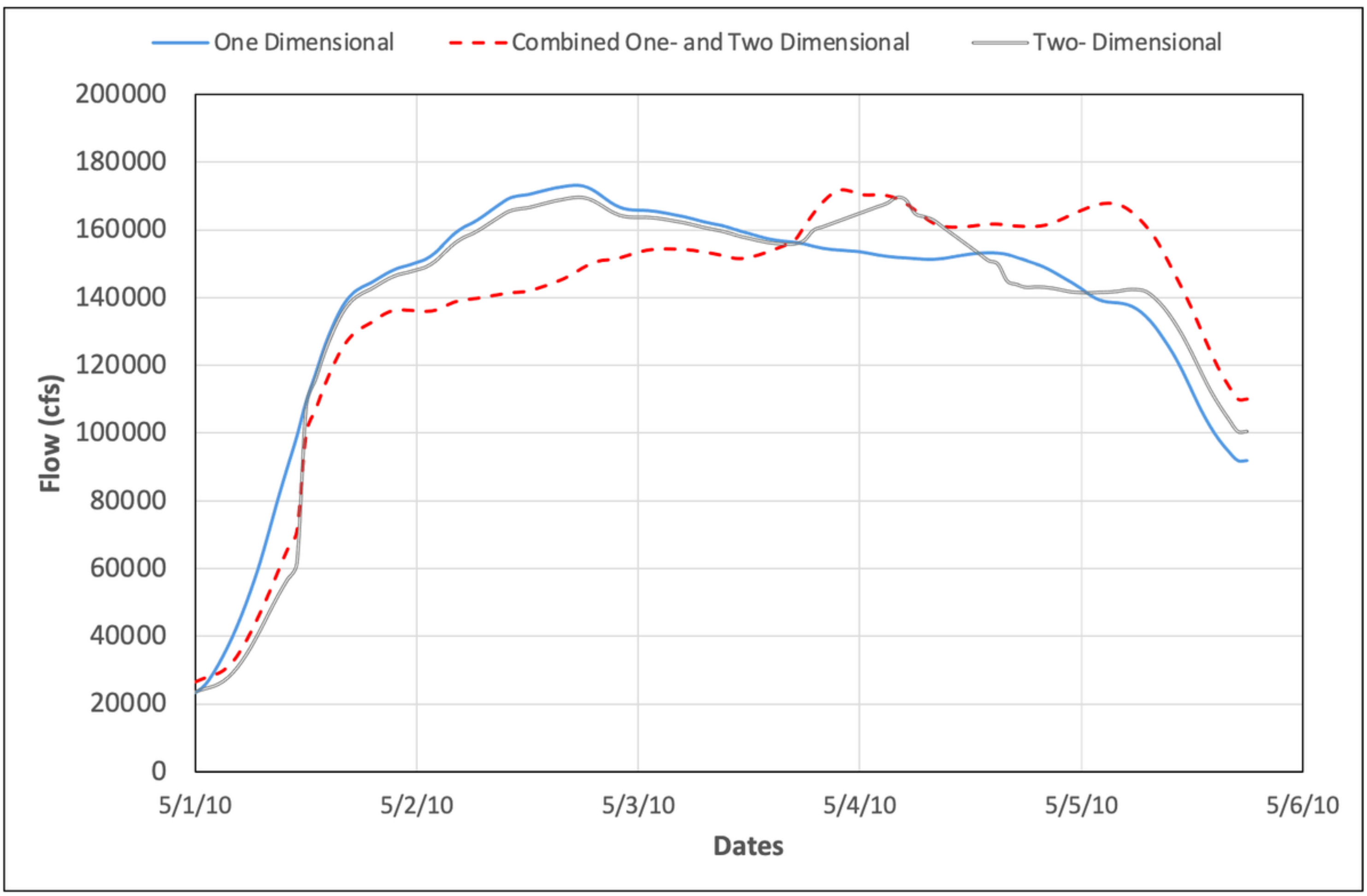

Figure 13

Optimized Discharges at Nashville for the May 2010 Flood Event for Three Scenarios of Unsteady Flow Modeling

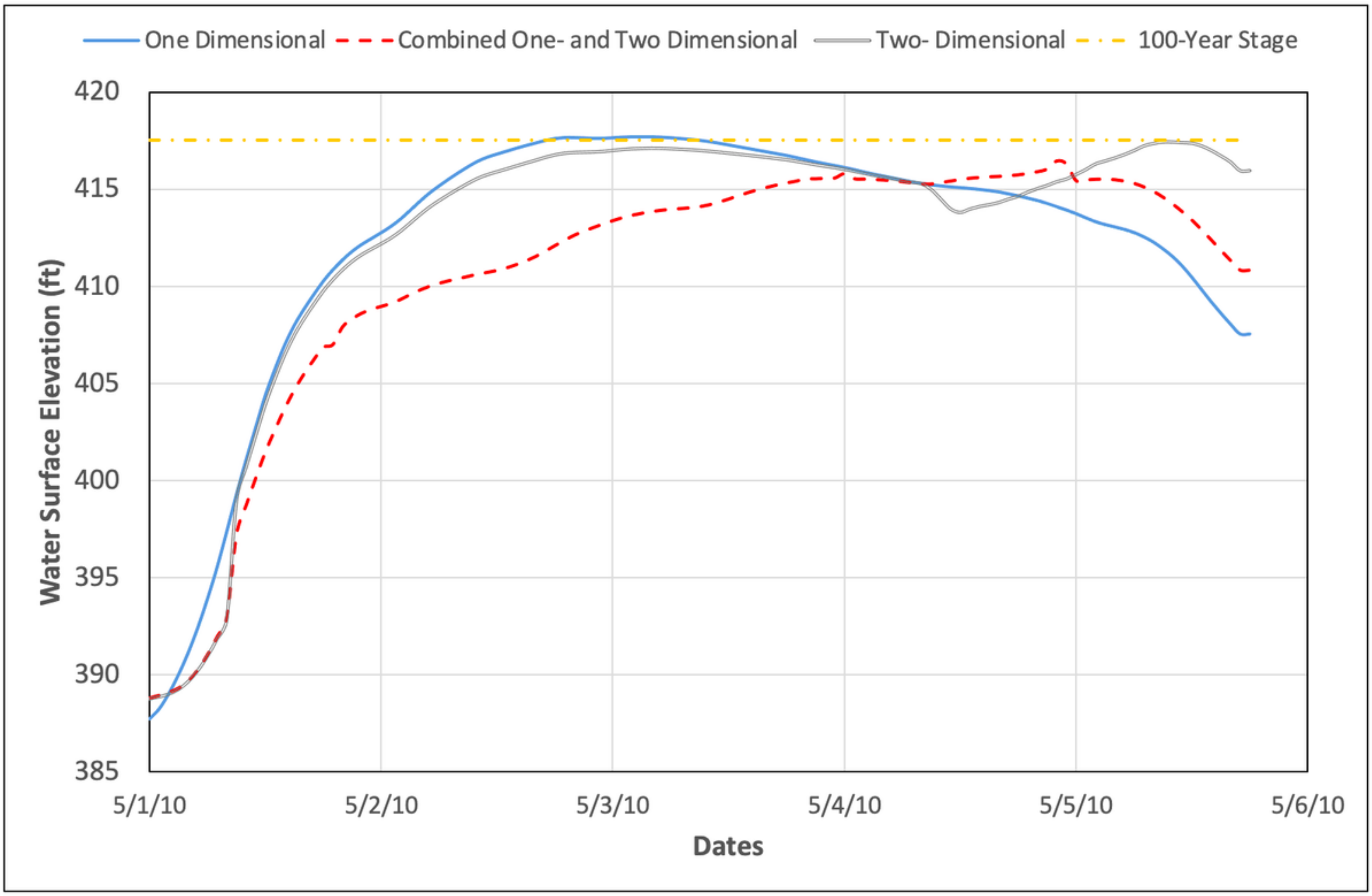

Figure 14

Comparison of 100-year and Optimized Water Surface Elevations for May 2010 Flood Event at Nashville for Three Scenarios of Unsteady Flow Modeling

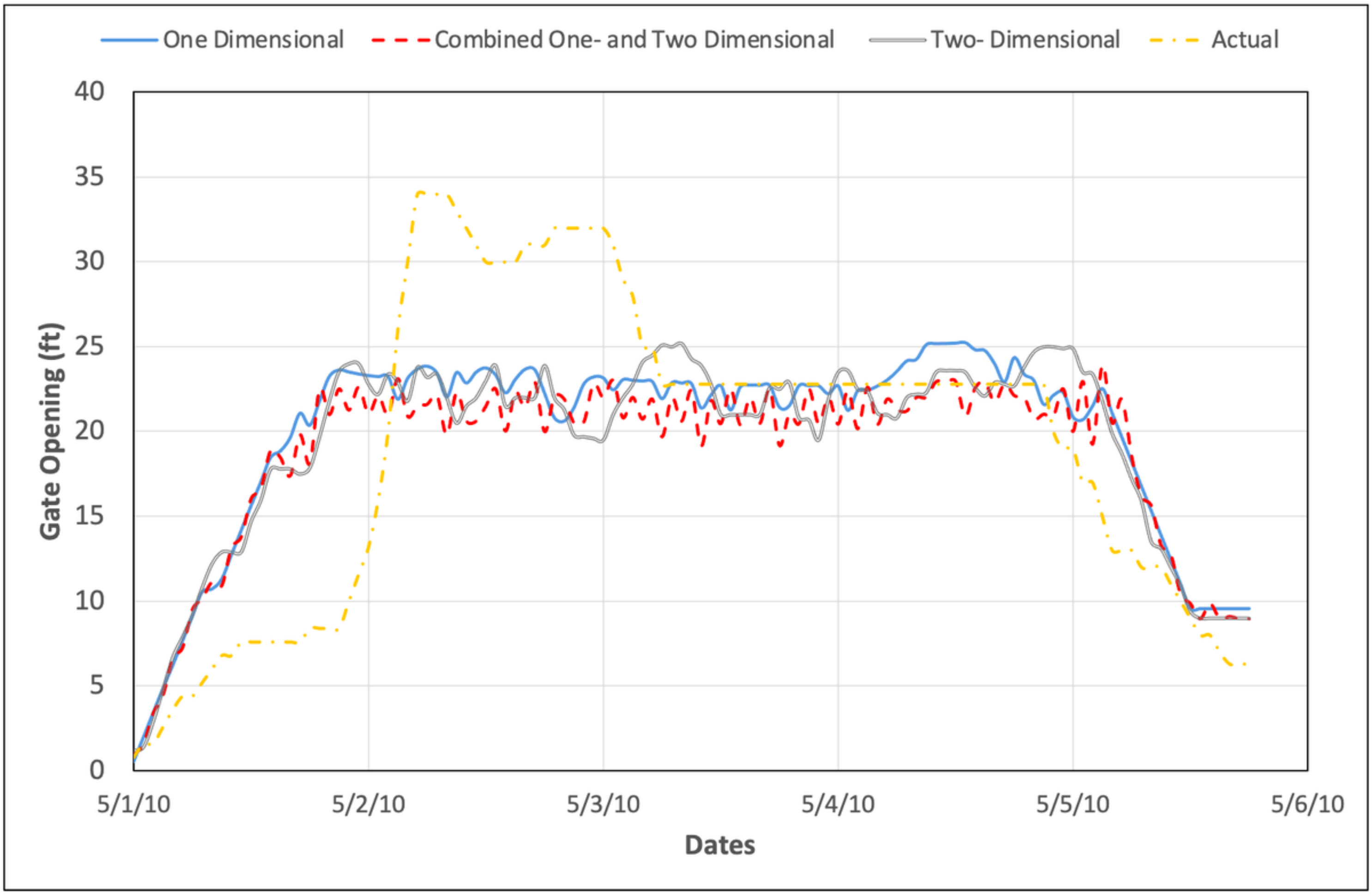

Figure 15

Optimized and Actual Operations (Flood Gate Openings) of the Old Hickory during the May 2010 Flooding Event

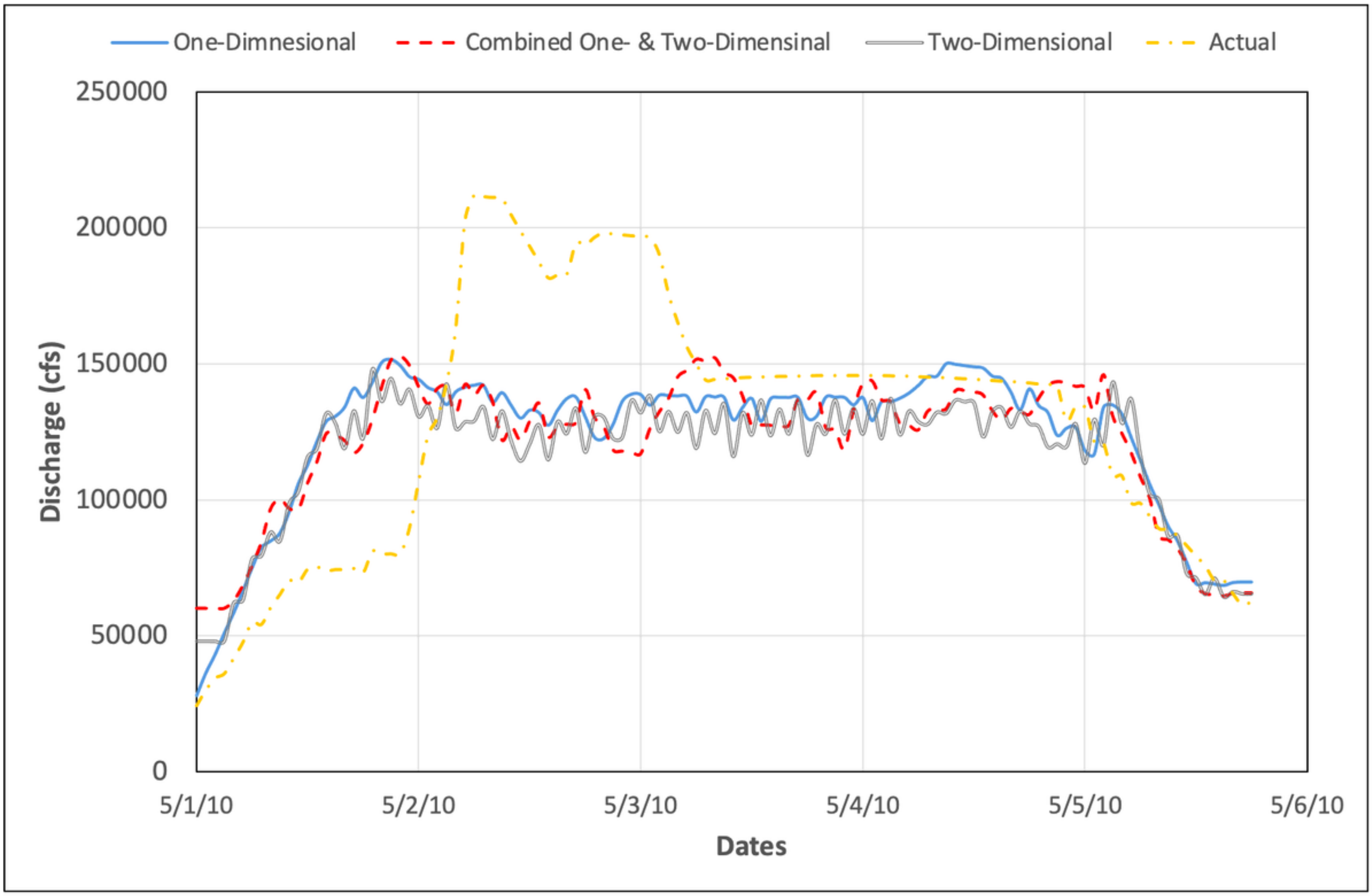

Figure 16

Optimized and Actual Releases at Old Hickory Dam During May 2010 Flooding Event

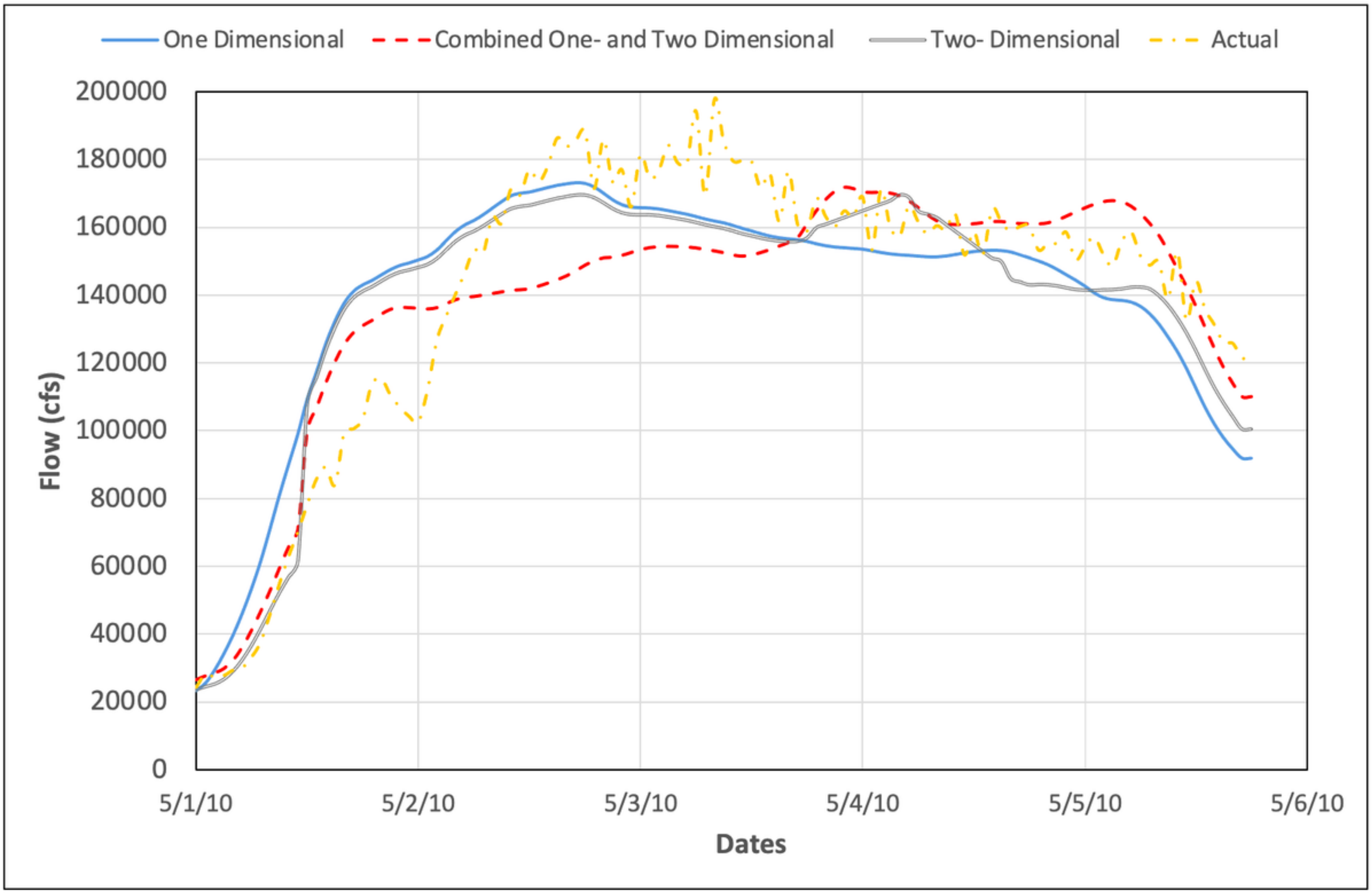

Figure 17

Optimized and Actual Flows at Nashville During the May 2010 Flooding Event